# Relating pain intensity of newborns to onset of nonlinear phenomena in cry recordings

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## Abstract

The cries of several full term newborns, recorded during blood sampling, were analyzed. Spectrograms showed the appearance of irregular patterns related to the pain assessed using the method of the DAN scale [3]. In particular, the appearance of Noise concentration Patterns (NP) in spectrograms was related to the increase of the pain suffered by the newborns. In this scenario, pain constitutes a bifurcation parameter for the vocal folds dynamic, inducing a Ruelle-Takens-Newhouse chaotic transition.

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## I. INTRODUCTION

The vocal folds, together with glottal airflow, constitute a highly nonlinear oscillator. The vocal folds are set into vibration by the lung pressure combined to the viscoelastic properties of the folds and the Bernoulli effect [8]. Normal voiced sounds appear to be nearly periodic, although small perturbations are important for the naturalness of voice. In the last years literature has concerned with observation and characterization of nonlinear phenomena in human and animal vocalization [5, 17, 21].Simulations show that the two mass model reproduces behaviors observed in natural vocalizations, including some irregular behaviors. Proposed by Ishizaka and Flanagan in 1972 [6], it was improved by Herzel and Titze in the last years [8, 13]. The model represents the vocal cords as a viscoelastic coupled oscillator. There exists a substantial evidence that vocal-fold vibration is a highly nonlinear process [10, 20], and the combined effects of nonlinear biomechanical events and aerodynamic events can produce rich irregular vibratory behaviors such as bifurcation and chaos [12]. Furthermore, the two-mass model is able to produce toroidal oscillations and chaotic transitions such as period doubling and Ruelle-Takens-Newhouse. These behaviors are strongly dependent on the variation of subglottal pressure and on the values of the elastic constants [19]. In the paper [7], Titze reported the equation of the natural oscillation frequencies $\omega_i$ of the model:

$$\omega_{1,2} = \sqrt{\frac{k_1 + k_c}{m_1} + \frac{k_2 + k_c}{m_2} \pm \sqrt{\left(\frac{k_1}{m_1 + m_2}\right)^2 + \left(\frac{k_2}{m_1 + m_2}\right)^2}} \tag{1}$$

Using the standard parameters suggested by Ishizaka and Flanagan he founds $f_1 = 120$ Hz and $f_2 = 220$ Hz. These values are inversely proportional to the weight of the vocal folds $m_i$ and proportional to the elastic constants $k_i$.

According to Barr et al. [1], the crying of the newborns is simultaneously a sign, a symptom and a signal. It is the infant's earliest form of communication but the significance of neonatal crying is still unclear. Pain scales [3] have recently been developed to discriminate levels of pain suffered by newborns but the direct relationship between the nature of crying and effective pain suffered is rarely considered in medical studies.

Chandre [4] showed that it is possible to describe and identify chaotic and irregular dynamics from spectrograms of irregular signals, while Mende [14] observed several irregular behaviors in spectrograms of newborns cries. Subharmonics and chaotic patterns have been

found in cries of healthy infants as well as infants with various perinatal complications [15]. However the frequency and duration of episodes depended on the health status of the newborn. This may indicate that brain control on the vocal apparatus is poor or not completely developed [14]. Dysphonia in infants was commonly related to several pathologies of the vocal cords, and a complete classification of these phenomena was made by Hirschberg [11]. Recently, Robb showed that phenomena like Biphonation, Harmonic Doubling, and F0 shift are common in healthy newborns too [18].

In this study we performed a time-frequency analysis on the vocalizations in order to find a relation between pain suffered and the presence of irregular and chaotic dynamics in the signal. We assessed whether onset of potentially chaotic cry segments, present in spectrograms as noise concentration patterns (NP) was also related to the degree of pain suffered by newborns. A hypothesis is that onset of nonlinear phenomena may be correlated with the muscle contraction typical of suffering. Contraction causes large variations in the elastic constants of the tissues and determines different oscillating behaviors of the vocal folds.

## II. MATERIALS AND METHODS

Babies enrolled in this study were all healthy term babies; the painful procedure was a heel-prick performed between 24 and 48 hours of live for clinical screening purposes (to assess phenylalanine and thyroid hormones plasma levels), and executed by two nurses following a standardized procedure.

Each baby was recorded with a Sony video camera, and a pain score was assigned on the DAN scale (Douleur Aiguë du Nouveau Né), a validated scale whose reliability (specificity, sensibility, accuracy and clinical feasibility) has been assessed[3]. The DAN score is obtained by scoring three items according to the extent they are present during the 30 seconds following the painful event: crying, arm and leg movements, grimacing. The pain scale is explained in table I and the total score ranges from 0 (minimum pain) to 10 (maximum pain). Recordings from 40 newborns were divided into three groups, depending on their assigned DAN score:

1. Low pain, DAN=1-4. A group of 10 newborns.

2. Medium pain, DAN=5-7. A group of 15 newborns.

3. High pain, DAN=8-10. A group of 15 newborns.

The acoustic signals were obtained by an analog recorder and time series of about 900 msec., corresponding to the first cry and to the exact moment of the cut, were extracted from each recording. Both power spectrum (PS) and phonograms were computed using a window of 1024 samples and a superposition region of 512 samples. For completeness, for every cry episode, we have collected three bawls, giving a greater importance to the first one, and using the other two for completeness. In fact, only the first cry is directly related to the painful event. We did not considered the successive cries because they were far from the sample, the effect of pain was reduced, and the successive shouts might be related to fear or angry.

## III. RESULTS

All the spectra were characterized by high values of the harmonics, with frequencies sometimes over the 10KHz, uncommon in adults, but explainable considering that the natural oscillation frequencies are inversely proportional to the masses of the vocal folds. We were interested in the detection of the irregular patterns known in literature as *Noise concentration patterns* (NP), directly connected to the onset of chaotic oscillations [9]. Other behaviors, such as vibrato, biphonation and $F0$ shift, that sometimes arise in newborns and infants cry and non-cry vocalization were not considered as irregular in this particular context.

### A. Low DAN (1-4)

Figure 1 shows the time series, the power spectrum and the spectrogram of a cry assessed with a low DAN score. The figure is representative of the other cries analyzed. The power spectrum and the spectrogram reveal the periodic nature of the vocalization emitted. In particular, phenomena such BP and $F0$ shift are present in all the other signals, but noise patterns are completely missing. Summarizing we have inspected 10 cries from 10 different newborns: all the cries were periodic, and no NP were detected. The inspection of the successive shouts showed the same regular patterns.

### B. Medium DAN (5-7)

The main feature of this class of cries is the drastically deduced number of harmonics and, as shown in figure 2 the presence of two different main frequencies, $f_1 = 245$ Hz and $f_2 = 1403$ Hz, their linear combinations $2f_2 - f_1$ and $2f_2 + 3f_1$, and some intermittent concentrations of NP. In time, as shown in figure 2(a), the pattern of the signal is more aperiodic, and the amplitude variations are an effect of the irregular oscillations. The presence of two different frequencies is usually related to aperiodic, but not chaotic, oscillations. This behavior is known as *torus-2* oscillation, and is the first step of the Ruelle-Takens-Newhouse transition [16], also reported for the vocal cords [9]. All the cries belonging to this class have the same characteristics discussed above.

### C. High DAN (8-10)

When the DAN score is high, the spectra and the phonogram are like those in Figure 3, showing large zones of NP without a clear fundamental frequency. The appearance of the signal in time (Figure 3(a)) is typical of irregular oscillations, and both in PS and spectrogram (Figures 3 (b) and (c)) are visible large concentrations of NP around two large indistinct frequency bands, usually referred to chaotic segments. All the cries belonging to this class have the same spectrographic characteristics.

Summarizing, the increase of pain induces a transition in the oscillation of the vocal folds of the type limit *limit cicle→torus 2→chaos*. Since the onward transition (caused by pain increase) is not obtainable for the same newborn, we performed a spectrogram analysis on the high DAN assessed cries, in order to find the inverse transition. Figure 4 reports the spectrogram of a 6 seconds cry consisting of three shouts. The recording begins with the sampling cut (0 sec.). The first shout is 4 seconds long, while the other two are about 1 second long. It must be pointed out that in the first shout is clearly visible the inverse transition from NP (0-900 msec.) to periodic behavior (from about 1.4 sec.) through a torus-2 oscillation (900 ms-1.4 sec.).

## IV. CONCLUSIONS

It was possible to discern pain levels from the spectrograms. For DAN scores under 4 the vocalizations were characterized by periodic behavior. At medium DAN scores (DAN=5-7) the oscillation became more irregular, and the presence of toroidal oscillation was observed. At high DAN (DAN=8-10) values spectrograms were characterized by large bands of Noise concentration Patterns.

If we consider variations in the bifurcation parameters of the vocal folds system, especially lung pressure and the elastic constants of vocal fold tissues, and assume that pain causes muscle contraction and an increase in lung pressure [2], we can explain these results as distortion of the oscillating system caused by large variations in vocal fold tension and tissues constants of distressed babies. According to this hypothesis, an increase in pain induces a chaotic transition in vocal fold oscillation of the newborn, so that crying associated with pain is strictly related to noise patterns in the spectrograms. The inverse transition, induced by the decrease of pain, was observed in the cries of highly suffering newborns. Moreover, we proposed a method for the assessment of pain based only on the spectral characteristic of cry.

## V. ACKNOWLEDGMENTS

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**Figures**

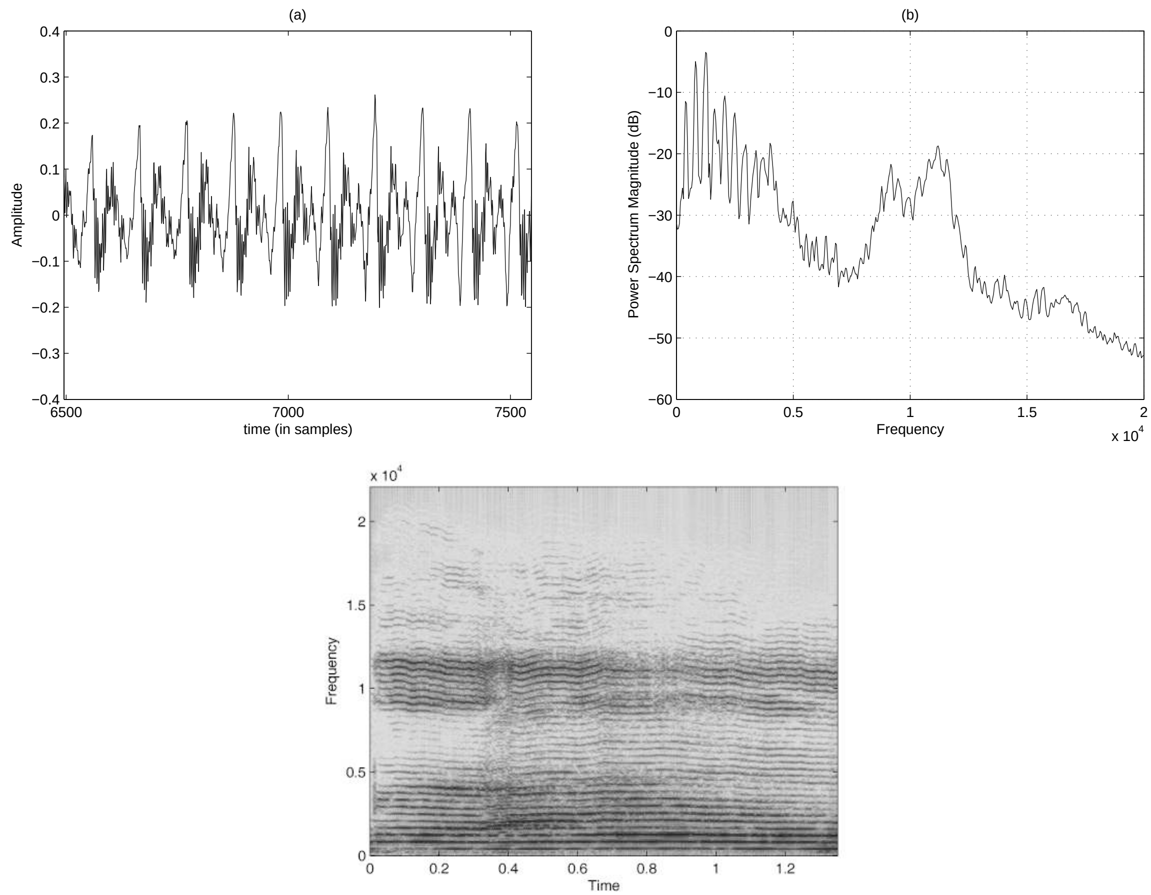


FIG. 1: Time and frequency analysis of a low DAN assessed cry.(a)A portion of about 1000 samples (22 msec.) showing the complex, but periodic, nature of the signal.(b),(c) Both PS and spectrogram confirm the periodic nature of the cry, the fundamental frequency is about 360 Hz, while some harmonics are over the 10 KHz.

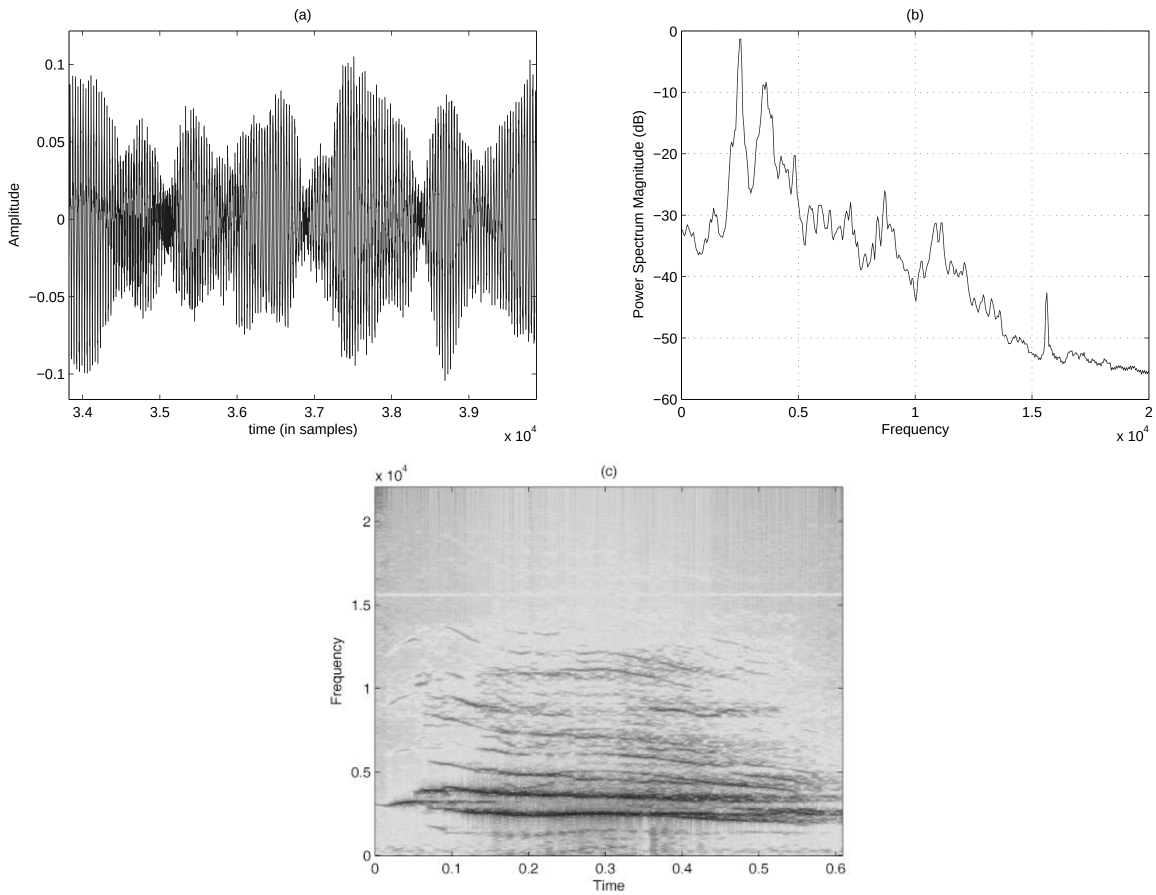


FIG. 2: Time and frequency analysis of a medium DAN assessed cry.(a) The signal looks more irregular, and the amplitude modulation is a symptom of a torus-2 oscillation. (b) In the PS are visible two main frequencies: $f_1 = 245$ Hz and $f_2 = 1403$ Hz and their linear combinations $2f_2 - f_1$ and $2f_2 + 3f_1$. This is usually referred to toroidal oscillations. (c) The spectrogram shows the two main frequencies and sob light concentrations of noise patterns.

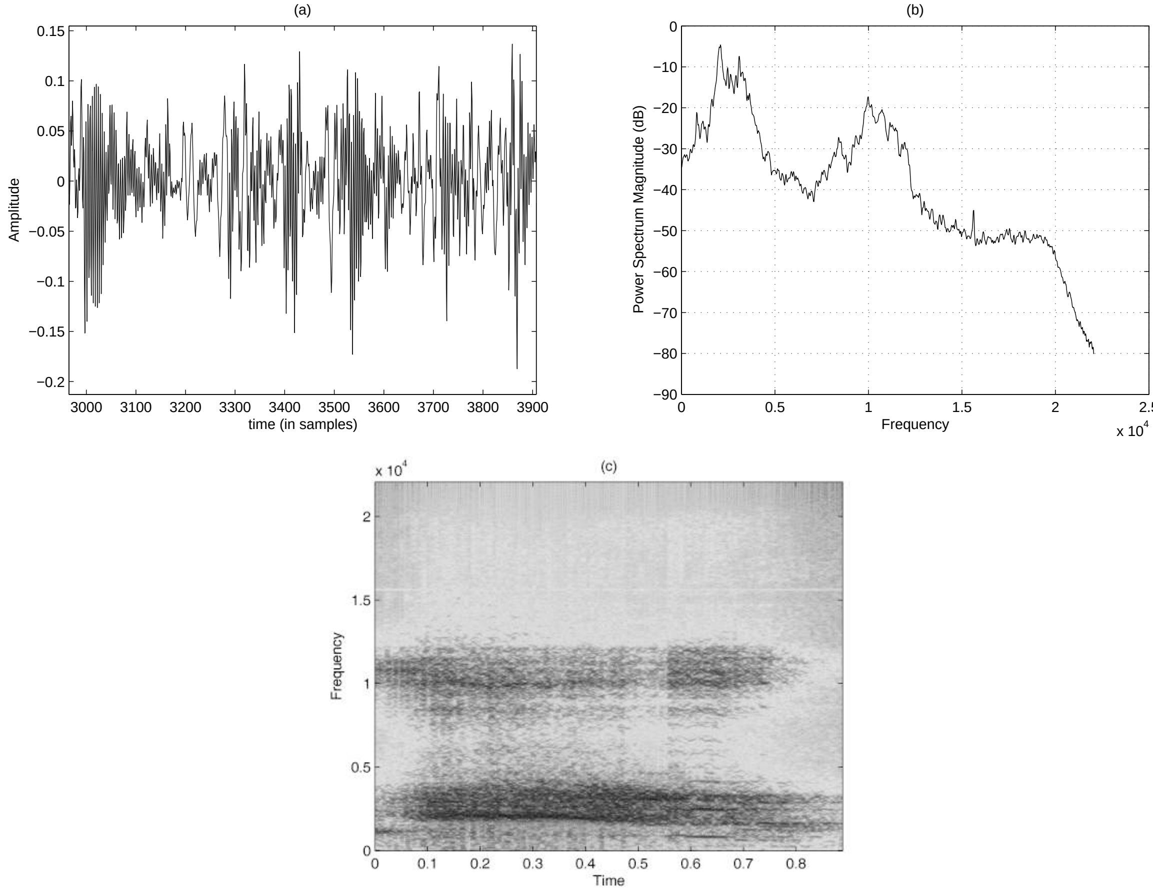


FIG. 3: Time and frequency analysis of an high DAN assessed cry.(a) The signal looks in time completely irregular, with concentrations of high and low amplitude spikes and strong variations in the period. (b),(c) Both PS and spectrogram confirm the irregular nature of the signal, which may be considered chaotic. In the PS is not possible to individuate any main frequency while the two large peaks are referred to the two NP bands in the spectrogram.

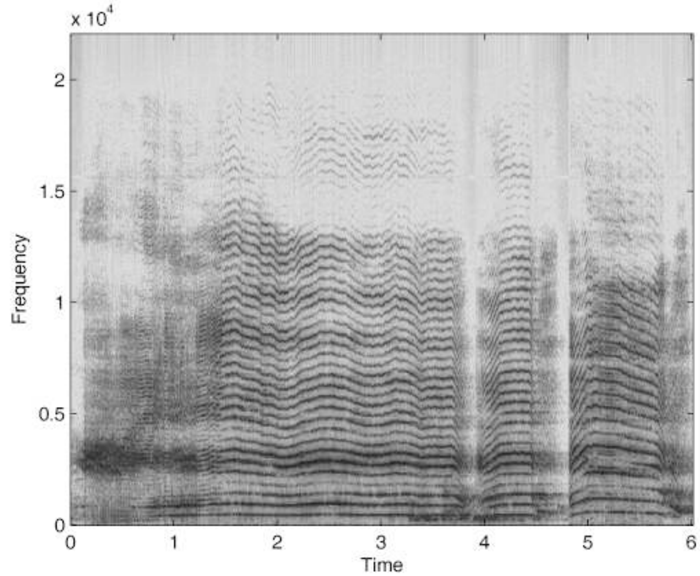


FIG. 4: Observation of the inverse transition *chaos→torus-2→limit cycle* in the spectrogram of a 6 seconds high DAN cry. Here are reported the first three shouts while the moment of the sampling cut is at 0 seconds. In the time window 0-900 ms are only visible the two NP bands. In the region 900-1400 msec. are clearly visible the two main frequencies of the toroidal oscillations, after that, the cry becomes regular. This inverse transition is due to the effect of cry on the organism.

**Tables**

TABLE I: DAN: behavioral acute pain-rating scale for neonates

| Measure | Score |
|---|---|
| **Facial Expressions** | |
| Calm | 0 |
| Snivels and alternates gentle eye opening and closing | 1 |
| Determine intensity of one or more of eye squeeze, | |
| brow bugle nasolabial furrow | |
| Mild, intermittent with return to calm | 2 |
| Moderate | 3 |
| Very pronounced, continuous | 4 |
| **Limb movements** | |
| Calm or gentle movements | 0 |
| Determine intensity of one or more of | |
| the following signs: pedals, toes spread legs tensed and pulled up, | |
| agitation of arms, withdrawal reaction | |
| Mild intermittent with return to calm | 1 |
| Moderate | 2 |
| Very pronounced, continuous | 3 |
| **Vocal expressions** | |
| No complaints | 0 |
| Moans briefly; for intubated child, looks anxious or uneasy | 1 |
| Intermittent crying; for intubated child, | 2 |
| gesticulations of intermittent crying | |
| Long-lasting crying, continuous howl; | 3 |
| for intubated child gesticulation of continuous crying | |